The Local Group as a test of cosmological models

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Abstract

The dynamics of Local Group and its environment provide a unique challenge to cosmological models. The velocity field within $5h^{-1}$ Mpc of the Local Group (LG) is extremely "cold". The deviation from a pure Hubble flow, characterized by the observed radial peculiar velocity dispersion, is measured to be ~ 60km s^{-1}. We compare the local velocity field with similarly defined regions extracted from N-body simulations of Universes dominated by cold dark matter (CDM). This test is able to strongly discriminate between models that have different mean mass densities. We find that neither the $\Omega = 1$ (SCDM) nor $\Omega = 0.3$ (OCDM) cold dark matter models can produce a single candidate Local Group that is embedded in a region with such small peculiar velocities.

For these models, we measure velocity dispersions between 300-–700km s^{-1} and 150–300km s^{-1} respectively, more than twice the observed value.

Although both CDM models fail to produce environments similar to those of our Local Group on a scale of a few Mpc, they can give rise to many binary systems that have similar *orbital* properties as the Milky Way–Andromeda system.

The local, gravitationally induced bias of halos in the CDM "Local Group" environment, if defined within a sphere of 10 Mpc around each Local Group is ~ 1.5, independent of Ω. No biasing scheme could reconcile the measured velocity dispersions around Local Groups with the observed one.

Identification of binary systems using a halo finder (named Skid (hhtp ref: http://www-hpcc.astro.washington.edu/tools/DENMAX)) based on a local density maxima search instead of a simple linking algorithm, gives a much more complete sample. We show that a standard "friend of friends" algorithm would miss about 40% of the LG candidates present in the simulations.

1 Introduction

Galaxies are observed to lie in a wide range of environments, from rich virialized galaxy clusters, to small groups that contain only two galaxies. The most "typical" galactic environment is a group that has a total luminosity of about $6L_*$, where L_* is the characteristic break in the galaxy luminosity function (Moore, Frenk & White 1993). (For $H_0 = 50$km s^{-1} Mpc^{-1} , $L_* \approx 4 \times 10^{10} L_\odot$ in the B band) The LG is a very typical small galaxy group, dominated by the Milky Way - Andromeda binary system and with over two dozen smaller satellites; the total luminosity is about $2.5L_*$.

Although the LG is not virialized and appears to reside in mildly overdense region of the Universe, the nearby larger Virgo cluster and the presence of the filamentary local supercluster, which itself connects to the Great Attractor (e.g., IRAS density field; Strauss *et al* 1992), creates a complex gravitational tidal field.

Measuring galaxy masses and Ω using Local Group dynamics has a rich history. Applying the timing argument to the Milky Way and Andromeda (Kahn & Woltjer 1959), a lower limit on mass of order 3×10^{12}M$_\odot$ is recovered using the radial infall solution. The retardation of nearby galaxy velocities from a pure Hubble expansion was used by Giraud (1986) and Sandage (1986) who both concluded that the mass of the Local Group must not be larger than a few times $10^{12} M_\odot$. On a larger scale, the LG motion towards the Virgo cluster, has been estimated to be between 85km/s (Faber & Burstein 1988, modeling the local velocity field with the Great Attractor) to 350km/s (with an average infall velocity of 250 ± 50km/s (the error is indicative of both the differences in different analyses and the internal measurement errors; Yahil *et al* 1980; Aaronson *et al* 1982; Dressler 1984; Kraan-Korteweg 1985; Huchra 1988). This value has been used to constrain Ω, on a scale of 10h^{-1} Mpc , yielding a fairly large acceptable range of Ω from 0.2 to 1.0, due to large uncertainties on both the observed Virgocentric infall motion itself and the mass density distribution in the region (Cen 1994). Peebles (1989a) calculates the orbits of the nearby galaxies using the "least action principle", assuming that peculiar velocities at high redshifts are negligible, and then integrating orbits forwards to try and reproduce their present day positions and velocities. Using only the LG members, both high and low Ω solutions are equally likely, but when galaxies out to 4000km s^{-1} are used a low value of Ω is preferred (Peebles 1995; Shaya *et al* 1995). Numerical simulations have played an important role in evaluating and testing these methods. Similar environments can be extracted from large N-body simulations and the same techniques can be applied to the "observed" information and the results compared with the true properties (Bushouse *et al* 1985; Moore & Frenk 1990; Kroeker & Carlberg 1991; Schlegel, Davis & Summers 1994, SDS thereafter; Cen 1994; Branchini & Carlberg 1994). Typically,

errors in the mass estimators are at least a factor of 2. The uncertainties result from a lack of the full velocity information, complex gravitational fields generated by surrounding structure and the assumption that the mass in halos has always been constant with time (Dunn & Laflamme 1995).

The interplay between fluctuations on different mass scales can be captured using large-scale N-body simulations hence the latter are ideally suited for studies of this nature. Because of its proximity, we know a great deal more about our Local Group than for any other galaxy group, e.g., the true distances and peculiar velocities are known for many of the nearby galaxies. Peebles has often emphasized using the Local Group to constrain cosmological models, and noted that both the galaxy distribution and the local velocity field may provide a challenge to current models (Peebles 1989b).

The "coldness" of the local Hubble flow can be quantified by measuring the dispersion (or rms) of the observed peculiar velocities around the mean local Hubble flow. Using 31 galaxies outside of the Local Group but within $5h^{-1}$Mpc, SDS (1994) find a value of 84 km s^{-1} (60km s^{-1} when distance errors are kept into account). A similar value was also obtained by Giraud (1986). This remarkably cold velocity field is only a local effect, and we do not know if it is a property of "Local Group" environments in general. Averaged over larger volumes of the Universe, the mean pairwise dispersion of galaxies increases to a few hundred km s^{-1}on the same scales if IRAS galaxies are used (Fisher *et al* 1994) to almost 700 km s^{-1}if a sample including more galaxies in clusters is used (Marzke *et al* 1995, Guzzo *et al* 1996, Somerville, Davis and Primack 1996). The fact that there are no nearby blue-shifted galaxies within a sphere of 5h^{-1} Mpc is another indicator of a fairly uniform Hubble flow. SDS searched for Local Group candidates in N-body simulations of CDM and mixed dark matter (MDM) Universes and concluded that the MDM model provides more candidates because the peculiar velocities are suppressed by the free streaming of the hot component. However, two major drawbacks of that work are the small volumes that were simulated and rather than defining Local Groups as binary systems, single galaxies in low density regions were selected instead.

In this paper we use high resolution large-scale N-body simulations, that resolve single L_* galaxy sized halos with hundreds of particles, while sampling a volume sufficiently large to contain hundreds of such halos. This allows us to construct large samples of "Local Groups" identified in a more robust and realistic way, such that they are a better match to the local dynamics and environments of our Local Group. We identify binary groups starting from a halo catalog built using a new halo-finding algorithm that eliminates the intrinsic biases produced by friend-of-friends algorithms. The peculiar velocity fields surrounding these mock LGs extracted from both high and low Ω CDM Universes are then compared with the real observed data. Our aim

is to determine if a Universe dominated by CDM can produce candidate sites that could host the Local Group galaxies, as well as matching the local velocity field. We shall also use these candidate LGs to test the "Virgo-centric infall" technique for measuring Ω.

2 The N-body simulations

Our simulations were performed using PKDGRAV (Dikaiakos & Stadel 1995, Stadel & Quinn 1997), a portable parallel treecode that supports true periodic boundary conditions, required for simulations of cosmological volumes. Although the simulations here would be considered fairly large by current single processor standards, they represent relatively small investments of "wall clock" time (~ 140 hours), using PKDGRAV on 64 processors of a CRAY T3D parallel computer.

We ran two simulations: a CDM $\Omega = 1$, h = 0.5, $\sigma_8 = 0.7$ model (SCDM) and a CDM $\Omega = 0.3$, h = 0.75, $\sigma_8 = 1$ model (OCDM) with zero cosmological constant. Each simulation cube is 100 Mpc on a side with both using 144^3 particles and a spline kernel softening of 60 kpc (The spline kernel is completely Newtonian at 2 softening lengths). Since our goal is to identify galactic sized dark halos, not to greatly resolve their internal structure, this force resolution is adequate. We used 650 and 1000 timesteps in SCDM and OCDM simulations, respectively. The mass resolution is such that a well resolved halo (30 particles) has a circular velocity of 110 and 90 km s^{-1}in the two models. We can therefore resolve halos that are associated with galaxies that have luminosities as low as 5% of an L_* galaxy.

The adopted SCDM and OCDM models are known to be "wrong", *i.e.* they cannot satisfy all of the observational constraints over a wide range of scales (for a review see Ostriker 1993). However, they are sufficiently realistic and in many aspects match observations very well so that they have been used frequently as convenient testbeds for "benchmarking" other simulations or for comparative studies. The normalizations we have used for both models are roughly correct in terms of reproducing the correct abundance of rich galaxy clusters (Bahcall & Cen 1992; Oukbir & Blanchard 1992; Viana & Liddle 1995; Kochanek 1995; Eke, Cole & Frenk 1996; Bond & Myers 1996), although the amplitude of the SCDM model may be slightly too high. Note that, while the OCDM model is approximately COBE-normalized (Gorski *et al* 1995), the value of σ_8 for a COBE-normalized SCDM model would be twice what we use here (Bunn, Scott, & White 1995). However, a slight tilt ($0.1 - 0.2$) from the Harrison-Zeldovich spectrum ($n = 1$) would suffice to make the SCDM in accord with both COBE and galaxy cluster observations. In any case, our conclusion would not sensitively depend

on n and our two adopted models should give a good representation of the Universe on small to intermediate scales.

3 Finding halos and local group candidates

The local overdensity can be determined using the complete catalogues of IRAS galaxies. Although these galaxies avoid the centers of rich clusters, they trace the rest of the galaxy distribution very well (Strauss *et al* 1992). For the 1.2Jy survey, SDS calculate that $\delta\rho/\rho \sim 0.25$ for a 5h^{-1} Mpc sphere centered on the Local Group, normalized to the mean IRAS galaxy density. The current best estimate based on IRAS galaxies is $\delta\rho/\rho = 0.60 \pm 0.15$ for a top-hat sphere of radius 500km/s (Strauss 1996, private communication). Hudson (1993) uses a compilation of optical galaxy surveys to study the local density field and within the same volume he finds an overdensity of ~ 0.2. The agreement between the optical and IRAS surveys is encouraging.

Our simulations only follow the evolution of the dark matter component. It is expected that baryons condense and form galaxies at the centers of the dark matter halos, a premise that is supported by simple considerations of the relevant dynamical timescales or by numerical simulations that include a gaseous component (White & Rees 1978; Cen & Ostriker 1992,1993a,b; Katz, Hernquist & Weinberg 1992). Therefore for our purpose of locating LG halo candidates (not resolving their internal structure), what we need is an algorithm that can find dark halos within the simulation by grouping together particles in an appropriate manner. Throughout this paper we assume that a galaxy with an observed circular velocity, V_c, would be found in a dark halo that has a similar circular velocity.

Linking together all particles within a minimum distance using the classic friends-of-friends type algorithm (FoF) has the undesirable consequence of linking together binary pairs of halos. This pathology is avoided by using a grouping algorithm that "moves particles" towards local density maxima to identify halo membership (Gelb & Bertschinger 1994a; see Fig.1 & 2). A complete description of the algorithm, named Skid (hhtp ref: http://www-hpcc.astro.washington.edu/tools/DENMAX), is given in Stadel *et al* (1996). Previous analyses of binary halos must be regarded with caution since we find that almost twice as many binary systems are uncovered using the new algorithm; catalogues of binary halos created with friends-of-friends (http ref: http://www-hpcc.astro.washington.edu/tools/FOF) may be biased, for example, due to exclusion of close pairs.

The Skid algorithm breaks up clusters and finds individual halos orbiting within larger halos. In order to calculate the total mass of a larger halo, (for example to get

the mass within the collapsed region, neglecting any substructure) we must re–group the particle distribution using a FoF algorithm. This is particularly important when we are trying to determine the presence and mass of Virgo sized clusters that lie near candidate Local Groups.

The FoF linking length was set to select particles within overdensities > 125 with respect to the critical value, which is the overdensity at the virial radius calculated using the spherical infall model (Gunn & Gott 1972). The density field for Skid was obtained by smoothing the particle distribution with a spline kernel over the nearest 32 neighbours for each particle. All particles with a local density larger then 57 times the critical density (the local density at the virial radius in an isothermal sphere) were then regrouped into halos. To avoid spuriously small halos due to the granularity of the particle distribution, halos within 3 times the softening length of each other were linked together, which sets the minimum separation (180 Kpc) between galaxy members in our binary samples. This is not a problem as we are interested mainly in binaries with separations larger than that.

No restrictions were placed on the local environment of the candidates, and we created three separate catalogues of binaries for each cosmological model with the following three different (increasingly stringent) constraints:

1) A generic sample of binary halos with separations $s < 1.5$ Mpc and circular velocities $125 < V_c/\mathrm{kms}^{-1} < 270$ (cat1).

2) A LG sample defined such that $s < 1.0$ Mpc, circular velocities $125 < V_c/\mathrm{kms}^{-1} < 270$, negative radial velocities and no neighbors within 3 Mpc with circular velocity larger than either of the two group members (cat2).

3) A LG sample defined as (2) but with the additional requirement that the binary halos must lie close (5-12h^{-1}Mpc) to a Virgo sized cluster with $500 < V_c/\mathrm{kms}^{-1} < 1500$ (cat3).

TABLE 1

LG abundance

Model	Skid	FoF
SCDM cat1	501	311
OCDM cat1	211	n/a
SCDM cat2	59	35
OCDM cat2	17	n/a
SCDM cat3	6	n/a
OCDM cat3	2	n/a

The FoF algorithm finds 40% less binary groups than Skid, a fact that reflects the pathology of the latter in linking close pairs of halos together. The OCDM model creates more than a factor of two fewer Local Group candidates than SCDM. The reason for this difference owes primarily to the different Ω in the two models, which is partially balanced by the adopted values of σ_8.

The lower Ω model contains fewer objects at a mass scale of $\gtrsim 10^{13} M_{\odot}$, *i.e.* the mass of the Local Group. This number density difference at this particular mass scale and at the present time is consistent (Governato *et al.* 1996) with an estimate made using the Press & Schechter theory (Lacey & Cole 1993).

In both models, the number density of binary halos increases with redshift, doubling with respect to the present at z $\sim$ 1. This is partially due to an increasing number of collapsing objects at the LG mass scale at earlier times and to the fact that it is easier for the LG binary systems to pass the isolation criteria from more massive groups.

4 Results

Is the Local Group a unique system in the Universe? If we occupied a special place then a measurement of physical quantities in our neighborhood would be less meaningful. Small galaxy groups are the typical environment that galaxies inhabit and Karachentsev (1996) argues that the Local Group is similar to other nearby groups of galaxies. A key test is the ability of hierarchical clustering models to produce structures similar to the LG at the present time, both in terms of producing binary systems similar to the Milky Way–Andromeda systems and in terms of reproducing

the characteristics of the surrounding environment of the LG.

We tested this by first selecting a generic binary sample with constraints looser than those we used to define the LG binary systems (using criterium (1)). The idea is to create a "control sample" and check first if our subsamples of LG binaries have extreme, or special dynamical properties with respect to this more general sample.

4.1 The dynamics of the binary systems

There are no discernible differences between the dynamical properties of the generic sample of binary halos and the sample of mock "Local Groups". The LG sample shows the same circular velocity distribution (which is directly related to the mass distribution) of the generic binary sample (Fig. 3). The distribution of radial velocities is consistent with the larger distribution of the generic sample (Fig. 4). Also, the observed radial velocity of the Andromeda-Milky Way system (-120km s^{-1}) is in very good agreement with our LG sample that only has the constraint of *negative* radial velocity.

Fig. 5 shows the relative radial peculiar velocities plotted against the separation of the halos. There is a weak trend in that closer pairs have larger negative velocities, and the SCDM model has a larger scatter than OCDM. Furthermore, there are many more systems in the SCDM model where the relative radial peculiar velocities are very large. We believe that this is a result of the stronger tidal field present in the SCDM model. A visual inspection of the most extreme cases reveals that pairs with very high negative relative velocities (larger than 400 km s^{-1}) have massive nearby companions, often just outside the exclusion zone (3 Mpc). For these systems, applying the "timing argument" will clearly yield false mass estimates.

As a measure of the ellipticity of the LG orbits, in Figure 6 we plot a histogram of the radial velocities divided by the absolute value of the relative (vector) velocity. Again, we observe no difference between SCDM and OCDM. However, the candidate LG halos tend to have radially biased orbits. This is probably due to the isolation criteria so that the motions are not strongly perturbed by nearby massive halos. However in all samples there is a wide spread in orbital eccentricities, with some pairs on fairly circular orbits. So, while these results support the picture of a Milky Way-Andromeda system being more likely on a radial orbit and at its first pericentric passage, orbits with smaller eccentricities cannot be excluded, at least on statistical grounds.

Producing binary system with *dynamical* characteristics similar to the LG is not a problem for CDM models. This reflects a generic success for CDM–like hierarchical

structure formation models that produce large numbers of late collapsing objects at a scale of $\sim 10^{13} M_\odot$. We shall show that this result is not true once we take into account the properties of the local environment of the model Local Group candidates.

4.2 The environment of Local Groups

The topology of the environments of the simulated Local Groups can be visualized via a series of MPEG movies that accompany this paper. In general, Local Groups prefer to inhabit low density regions, sometimes with an overdensity that is below average, or on the outskirts of clusters, but never in very dense environments (Fig. 7 & 8 and Movie 1). Also visible on a visual inspection is a tendency for the candidate Local Groups to reside in filaments and planes (Fig. 9, Movie 2). It would be interesting to quantify this statement by applying a statistic such as that used by Brandenberger *et al* (1993) to candidate systems in higher resolution simulations. Fig. 10 plots the histogram of local densities around each LG binary measured in a sphere of 10Mpc (h already accounted for). The OCDM distribution seems to be marginally more peaked around values close to the average density, while that of the SCDM is broader.

For each candidate Local Group we plot the overdensity within $5h^{-1}$ Mpc against the dispersion in peculiar velocities of all the *halos* within this region (Fig.11). Also plotted is the observed value for our Local Group. Each individual value was obtained fitting locally the value of the Hubble constant (starting from the smallest galaxy in the LG pair) and then subtracting the peculiar velocity of every halo previously identified. A $5h^{-1}$ Mpc sphere corresponds to different regions in velocity space for SCDM and OCDM because the two models have different values for the Hubble constant. However, we found no difference in our results when we used a sphere of 10 Mpc (no h dependence) centered on the LG's within the OCDM model. A more sophisticated approach might use a more detailed model of the Hubble flow close (within $\sim 2\mathrm{h}^{-1}$Mpc) to each LG binary. However, we have checked that the results do not change if galaxies within $2.5\mathrm{h}^{-1}$ Mpc from each LG are discarded, where this correction could be of some importance.

The OCDM candidates lie in a well defined region of this diagram, and all have higher peculiar velocity dispersions than measured. The SCDM groups have more scatter, and almost all of the points lie above those of OCDM. The same relation holds if the halo density is used instead of the mass density, implying that there is a tight (even if biased, see 4.4) relation between the halos and the mass distribution. Typically each sphere contains several tens of halos.

The observed dispersions were obtained after merging together and taking the

average value for all galaxies within groups. This is similar to measuring the dispersion in the Hubble flow using DM halos, as is done in this paper, because substructure within groups sized halos is erased due to overmerging (Moore et al 1996).

Our main result is that for SCDM, we find that for Local Group candidates at an overdensity of 0.2, the peculiar velocities of nearby halos have a dispersion between 300 – 700 km s^{-1}. OCDM candidates give candidates with dispersions in the range 150 – 300km s^{-1}, several times larger than the observed value. Neither of these models are able to produce a single LG with a local velocity dispersion comparable with the observed value. There is a trend for LGs living in underdense regions to be surrounded by a colder Hubble flow, however even in such regions the flow is hotter than the observed one. This places a strong constraint on both models, since even invoking a generous bias that would stretch the distribution of points in Fig. 11 along the x axis, would not lower the values of the measured velocity dispersions. If we use the new suggested value for the local overdensity (i.e. 0.6, as mentioned in paragraph 3) then the comparison with real data would be even worse for both CDM models.

Lower values of Ω might close the gap between the peculiar velocity dispersion surrounding Local Group candidates in the models and the observed value. Indeed, low values of Ω are inferred when the dynamics of galaxy clusters are considered. However, measurements of large scale streaming velocities indicate higher values, $\Omega \gtrsim 0.3$ (Nusser & Dekel 1993). Also, recent numerical studies of the cluster velocity field based on LG–like observers (Moscardini *et al.* 1996) favor $\Omega \gtrsim 0.4$ in CDM models.

4.3 Virgo-centric infall

The component of the Local Group's velocity towards the Virgo cluster can be used to infer Ω on a scale ~ 10 Mpc (see e.g., Huchra 1988 for a review). We define Virgo sized clusters as those halos identified by FoF with 1-d velocity dispersion in the range 550-750km s^{-1}, which yields 4 such "Virgos" in each of our volumes. As is also discussed below, FoF is better suited to identify clusters with a given mass. In this case we did not want to break each "cluster", i.e. each region within the overdensity of 57 in individual subclumps, as Skid would have done.

We apply a modified relation of the linear theory spherical infall model (Gunn 1978) including nonlinear effects (Yahil 1985, see also Villumsen & Davis 1986) to our model Local Groups that lie within 1000 km s^{-1} of a Virgo sized cluster:

$$\frac{\Delta Hr}{Hr} = -\frac{f(\Omega)}{3}\frac{\Delta\rho}{\rho}(r)[1+\frac{\Delta\rho}{\rho}(r)]^{-0.25}, \tag{1}$$

where Hr is the flow at radius r from the center of the Virgo cluster, ΔHr the deviation from the mean Hubble flow, $f(\Omega) \approx \Omega^{0.6}$, $\Delta\rho/\rho(r)$ the mean overdensity

inside the Virgocentric radius r. The last term in the right hand side of equation (1) reflects a fit to the nonlinear effects. The six LG candidates in the SCDM (Fig.12, panel (b)) simulations give a range of inferred mass estimates that differ from the true mass by at least a factor of 2, although the mean value is roughly correct. As OCDM has a larger Hubble constant, the physical volume around Virgos that is useful for estimating the Virgo infall is smaller and so we have only two candidates in this case. These would yield $\Omega = 0.05$ and 0.29 for observers in their Local Group vantage points (Fig.12, panel (a)). Similar conclusions were obtained by Bushouse *et al* 1985, Cen 1994.

Inaccuracies in the mass estimates using spherical infall theory arise from several effects. Infall velocities are not perfectly radial since the gravitational field on $10h^{-1}$ Mpc scales is very complex. Defining the center and peculiar velocity of a cluster is difficult since large pieces of substructure may be moving rapidly within a clusters halo. Skid will identify a largest subclump that may have a peculiar velocity with respect to the whole cluster between 500 – 1000km s^{-1}. The same thing may happen in the real case, as the Virgo cluster is itself a complex system with substructure and smaller groups that appear to be extended along the line of sight and can be broken up into several merging sub-groups (Bohringer *et al.* 1994). Therefore, we cannot expect to infer Ω with any significant precision using this technique for a single system. This also indicates that the observationally inferred value of Ω from Virgo infall analysis should be taken with caution.

4.4 Dark matter distribution and the Local group

The term "bias" has been coined to relate the global galaxy distribution to the underlying matter distribution. Simple physical arguments (Binney 1977; Rees & Ostriker 1977; Silk 1977) say that galaxies should form in regions with special properties: contracting regions of high density that are relatively "cool" should be favored sites. Statistical arguments (Kaiser 1984, Bardeen *et al* 1986) indicate that if galaxies form preferentially in density peaks, they are more strongly clustered than the mass. Brute-force approaches – direct hydrodynamic galaxy formation simulations that include both gravity physics and microphysics on which the above simple arguments are based, find that galaxies are more strongly clustered than matter (Cen & Ostriker 1992; Katz, Hernquist & Weinberg 1992).

It is interesting to determine if the distribution of galaxies in the environment surrounding LG binaries is somewhat biased with respect to the DM one, i.e. if $\delta\rho/\rho$ of halos is larger than $\delta\rho/\rho$ for the total dark matter distribution. In this case it is easier to measure the overdensities in spheres around each LG. (Fig.13). We choose a radius of 10 Mpc as representative of the LG environment, while still being in a

mildly nonlinear state.

We find that halos in the LG environment are slightly biased (b $\sim$ 1.5) with respect to the surrounding DM distribution. This result holds for both the SCDM and OCDM models, and is consistent with what is found for a population of bright galaxies in an SCDM Universe (Kauffmann, Nusser and Steinmetz 1996, Gnedin 1996, Cen & Ostriker 1992; Katz, Hernquist & Weinberg 1992). It is remarkable that the same amount of bias is found in the OCDM cosmology.

5 Discussion

We extracted Local Group candidates from large, high resolution N-body simulations of two CDM Universes with values of $\Omega = 1.0$ and 0.3. We then compared their properties and the velocity field around them with the real Local Group. To select the binary systems we used a new halo finder algorithm, based on local density maxima. We show that a binary sample identified with a standard "friend of friends" algorithm would miss 40% of them.

The internal properties of the binary groups we extracted are very similar in both models, even when we relax some of the constraints on the isolation, separation and radial velocities. Our result that the Local Group is not a "special" place in the nearby Universe *if it was formed in a hierarchical CDM context*, makes our location extremely useful for testing cosmological models since we can measure peculiar velocities and distances to many of the nearby galaxies.

However, we do find large differences in the nearby velocity fields of these models. These models yield dispersion velocities in the Hubble flow within a sphere of 5h^{-1} Mpc between 300–700km s^{-1} and 150–300km s^{-1} respectively. The observed value is 60 km s^{-1}. *Neither of these models can produce a single candidate Local Group with the observed velocity dispersion in a volume of 10^6 Mpc^3.*

As far as we know, the Local Group is not special in any way that could bias these results. We believe that our local overdensity is fairly well determined, to within a factor of two, and both IRAS and Optical surveys give $\delta\rho/\rho \sim 0.2$. Even if we lived in a highly underdense region such that $\delta\rho/\rho \sim -0.3$, our local Universe could *not* be reconciled with a low Ω CDM Universe.

Mixed dark matter models might do better than standard CDM (especially SCDM with a σ_8 normalization > 0.45, but they do not perform significantly better than the low Ω model considered here (SDS, their Table 1). However, the result of SDS is based on a set of simulations of a smaller region of space than ours and the problem of selecting realistic LG's was not addressed. We expect that a CDM $+\Lambda$ model

would give a value of the local velocity dispersions intermediate between SCDM and OCDM.

The distribution of galaxies in the LG environment is biased (b ~ 1.5) with respect to the DM distribution, this result is consistent with other work related to the more general galaxy distribution.

If we ran simulations at a higher resolution, we could resolve more smaller halos that are in general less clustered. At our present resolution we are resolving halos that might contain galaxies as luminous as the Large Magellanic Cloud. But it is unlikely that, on average, the bulk motion of very small objects will be significantly lower, were they properly resolved and identified, primarily because the distributions of galaxies are observed to be spatially unsegregated in terms of mass or luminosity. Therefore, we expect that a higher resolution simulation would not alter our conclusions significantly.

The inability for a CDM dominated Universe to produce any Local Group candidates with a cold flow reflects a long standing problem of this model if compared to the observed properties of the local Universe: the peculiar velocities of galaxies are too high on average (Gelb & Bertschinger 1994b) This evidence may actually suggest that, even when normalized to the cluster abundance, power in CDM–like models is too high at intermediate mass scales, the more responsible for peculiar velocities at scales of a few Mpc. However, power cannot at the same time be reduced at small, subgalactic scales, as it is necessary to produce structure at early epochs as the observed Lyman alpha clouds (Cen *et al* 1994; Zhang *et al* 1995; Hernquist *et al* 1996) or damped Lyman alpha systems (Mo & Miralda-Escudé 1994; Subramanian & Padmanabhan 1994; Kauffmann & Charlot 1994; Ma & Bertschinger 1994, Gardner *et al* 1996).

Finally, cosmic variance on scales larger than the volume of our simulations (10^6Mpc^3) might generate regions where the Hubble flow is substantially colder than average. Sommerville *et al.* (1996) analyzed simulations of the same size of ours and found a standard deviation in the pairwise velocity dispersion of about 150 km s^{-1}for different observers placed in the same cosmological volume.

Our results also suggest that is critical to obtain new, updated values for the peculiar velocities of nearby galaxies, as the problem of the coldness of the Hubble flow would be alleviated if the local velocity dispersion had been previously underestimated. More data should soon be available with the HST Key Project (Freedman 1994).

The next step for testing the various variants of the CDM model, which are currently considered to be the most viable family of models will be large scale galaxy

formation simulations. It will be necessary to include a detailed description of the physical processes including hydrodynamics, radiative processes (with possible inclusion of detailed radiative transfer process) and simple robust star formation prescriptions (Gelato & Governato 1996).

A failure of these models to reproduce the basic properties of the nearby Universe would probably imply that we are missing an important ingredient in our standard cosmological models. That could be our conception of the nature of the dark matter itself.

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Figure captions

Figure 1 The upper panel shows the density of the mass distribution of the SCDM simulation in a $5 \times 50 \times 50$ h^{-1} Mpc slice, higher densities are brighter colors. The lower panel shows the distribution of halos found by Skid, the colors are random.

Figure 2 A "Local Group" binary system found by Skid. The lines connected to the particle points show the trajectories towards the local density maxima. Note the small satellites between the two main galaxies.

Figure 3 A histogram of halo circular velocities of all the LG halos, plotted as a fraction of the total number. The dot-dashed red line are halos belonging to LG candidates in the SCDM simulation (a) The green dashed line are from the OCDM simulation (b) . The solid line in each panel shows the distribution of halos from the general samples from each simulation. Panel (c) compares the mass functions of SCDM and OCDM.

Figure 4 A histogram of relative radial velocities of the binary halos within the control sample of binaries (solid white lines) and Local Groups (dot-dashed red line are SCDM groups (a), dashed green line are OCDM groups (b)). Panel (c) compares the SCDM and OCDM distributions.

Figure 5 The relative radial velocities of the binary halos are plotted against their separation. Panel (a) are OCDM systems, green dots (stars in the b/w plot) are LG binaries and black dots are from the general sample. Panel (b) are SCDM systems, red open circles are LG binaries andblack dots are from the general sample.

Figure 6 The relative radial velocities of the binary halos divided by the total relative velocity are plotted as a histogram for the OCDM model (a) and SCDM model (b). The colors are as in Figure 3. Panel (c) compares the two models.

Figure 7 The density field in a $10 \times 50 \times 50$ h^{-1} Mpc slice is plotted for the OCDM simulation. Green boxes show the location of Local Group candidates in each model. The color scale has been stretched such that the plotted densities span a range between the average and 10^4 times the average value for each model. Since the models have the same phases in the initial conditions, with this scaling the structures appear very similar. However, the SCDM simulation has more massive halos.

Figure 8 Same for the SCDM model.

Figure 9 A model Local Group from the SCDM simulation that is located in a planar structure. This Group is featured in Movie 2.

Figure 10 A histogram of the overdensities of the LG environments (dot-dashed red line are SCDM groups, green dashed line are OCDM groups). The density is calculated on a sphere of 10 Mpc around each LG.

Figure 11 The dispersion of peculiar velocities from the local Hubble flow for each Local Group. Overdensity is measured in a sphere of 5h^{-1}Mpc. Red open circles are SCDM groups and green filled circles are OCDM groups. The observed value is plotted as a star.

Figure 12 The estimated value of Ω plotted against a convenient function of overdensity of the cluster-group region. Ω is calculated using the "Virgo-centric infall model" applied to two candidates from (a) the OCDM simulation (green full dots) and (b) for the six candidates in the SCDM simulation (red circles).

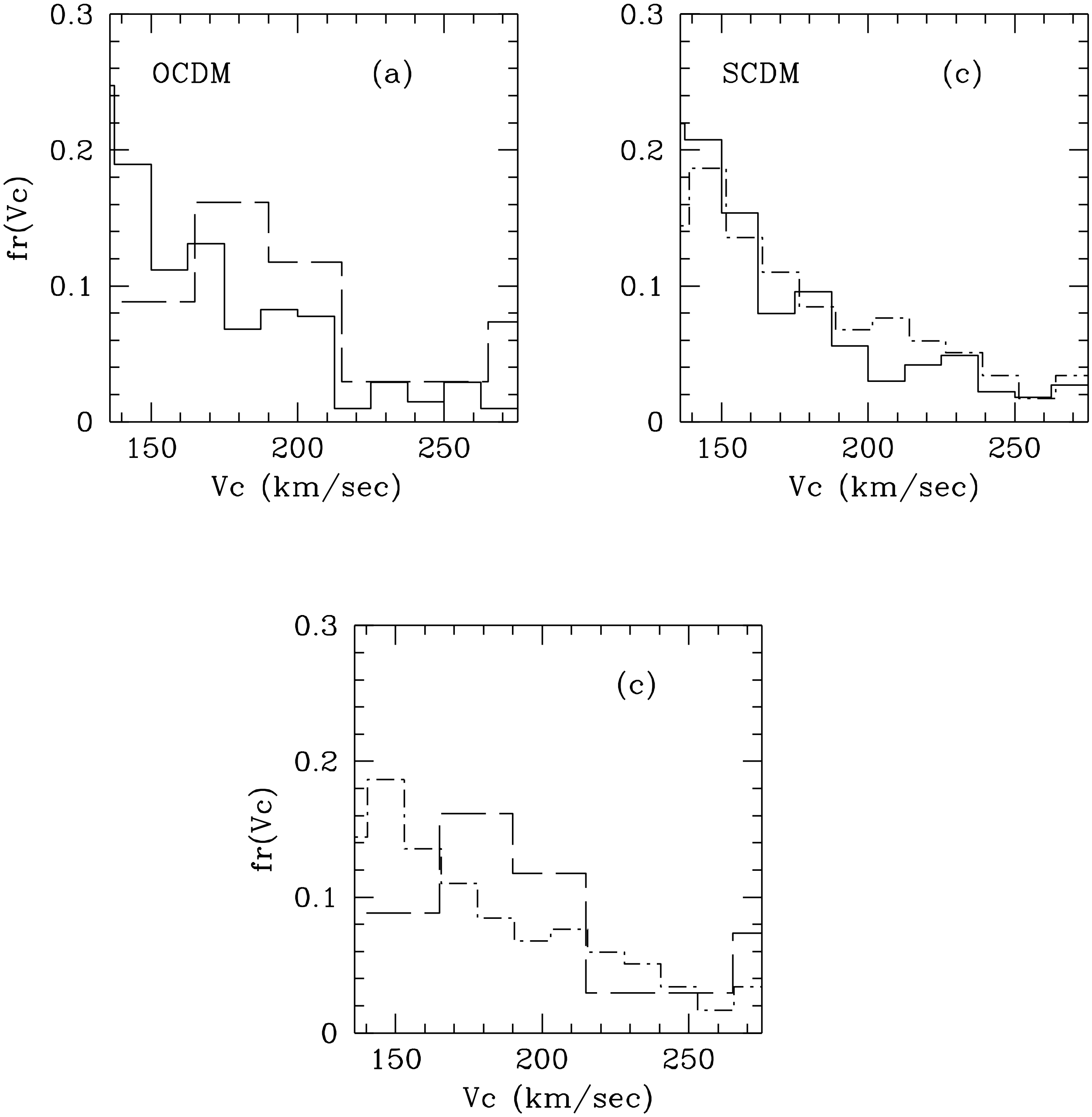
Figure 13 A plot of the bias in the halo distribution of each Local Group environment (red open circles are SCDM halos, green dots are OCDM halos). The line shows the relation that would be found when there is no bias.

Movie 1 This MPEG movie slices through the OCDM cube. Particles belonging to

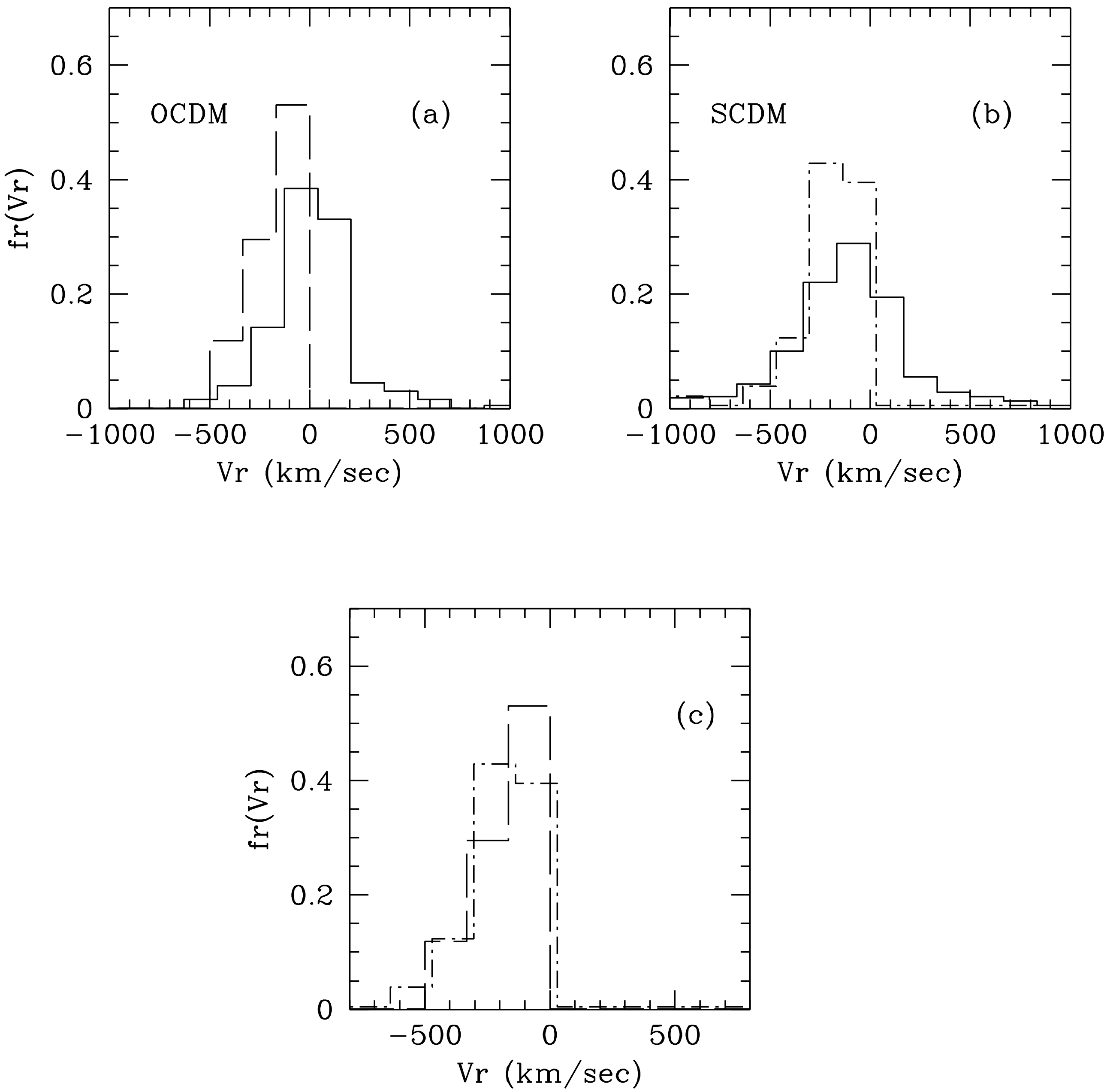
LGS are in green. Bright colors represent higher density regions. LGs hinabit a wide variety of environments, , but are preferentially located in filamentary or planary structures. The slice thickness is 5Mpc.

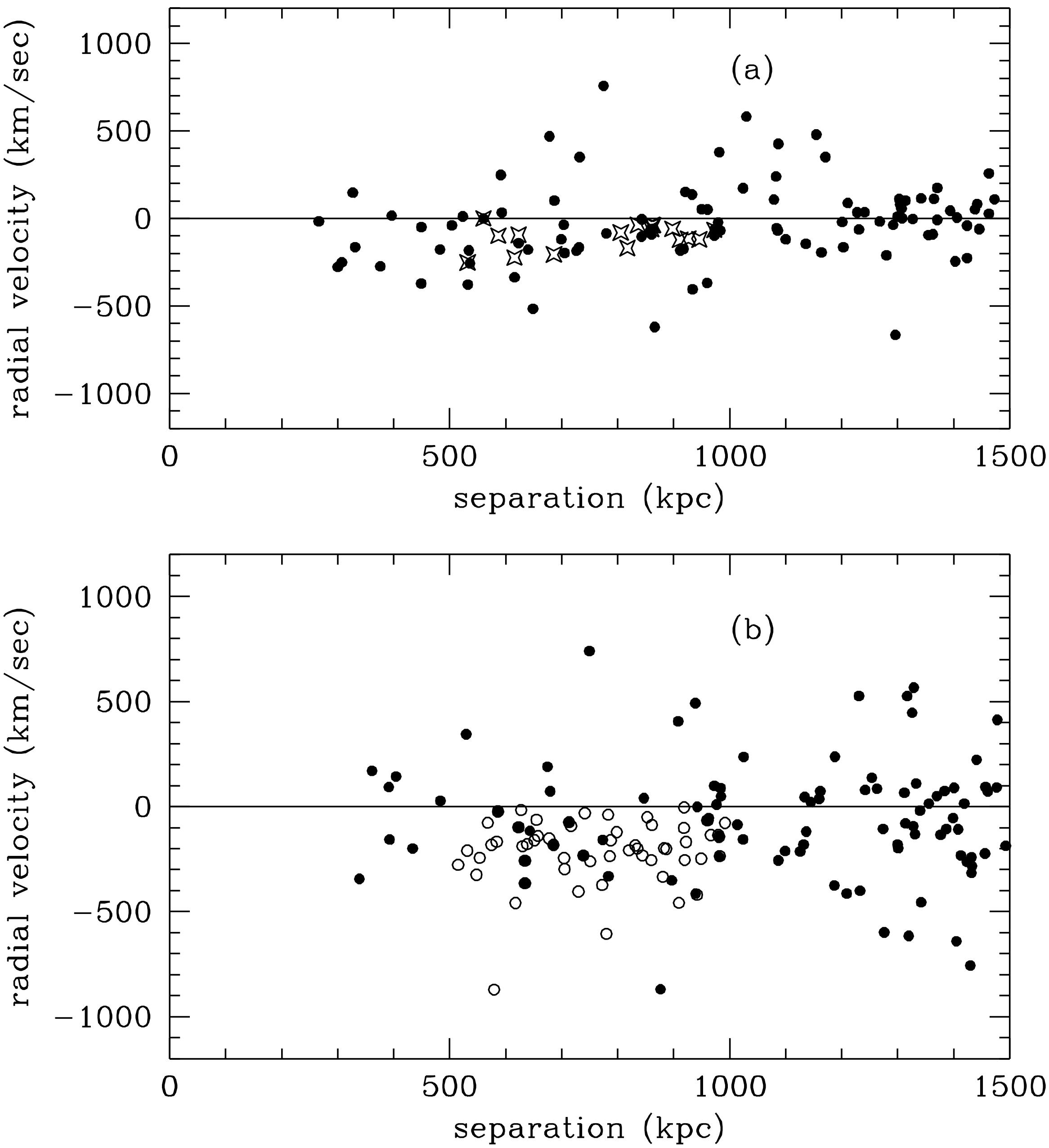
Movie 2 This MPEG movie shows a region of space centered on a LG extracted from the SCDM volume. The rotation shows clearly the planar structure in which the LG (LG particles are marked in green) is embedded. The complex network of filaments that forms the whole surrounding region is evident. The same filaments continue well outside the spherical region of space shown in the animation. The sphere diameter is 20Mpc.

Circular Velocity histogram

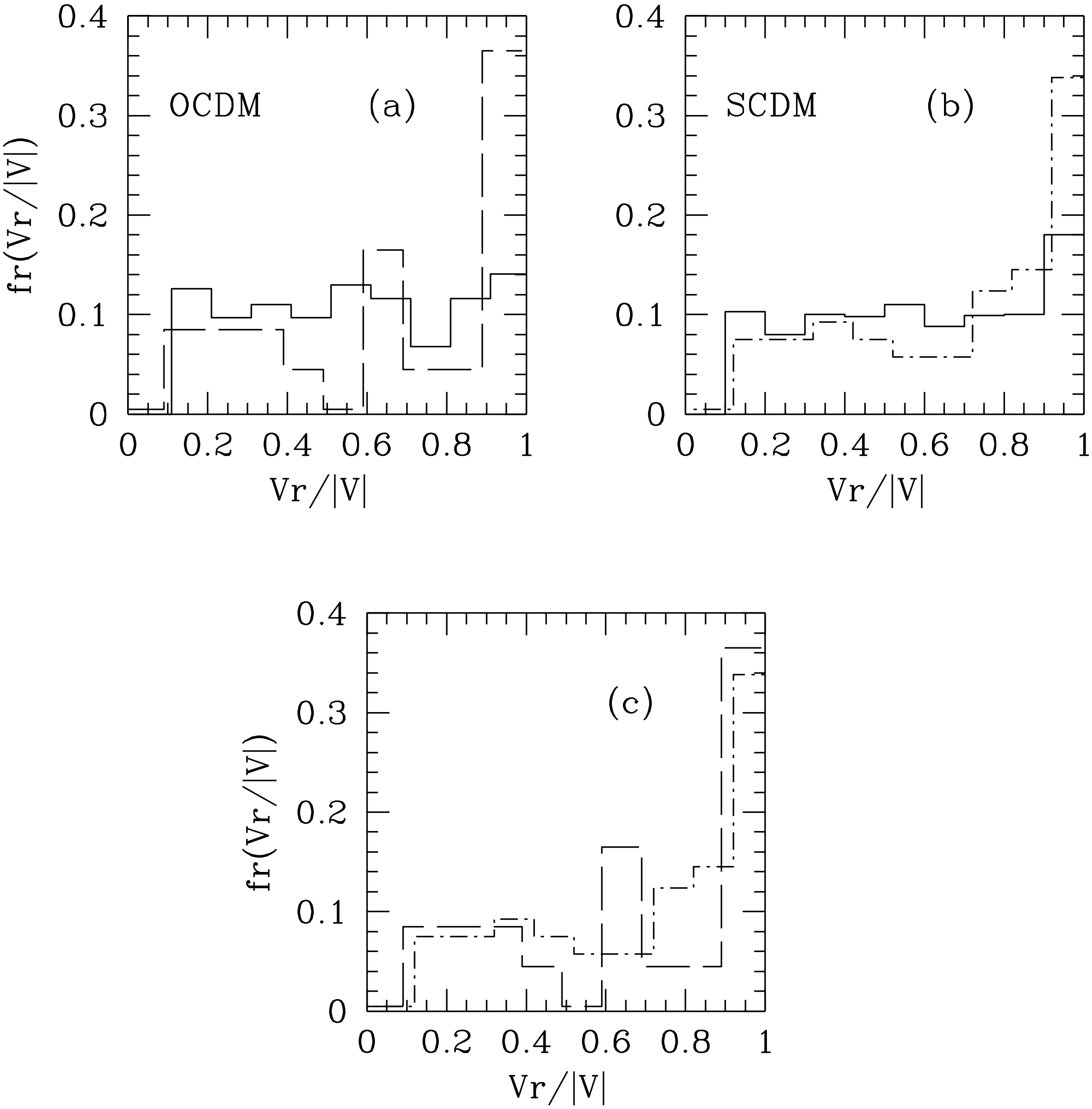


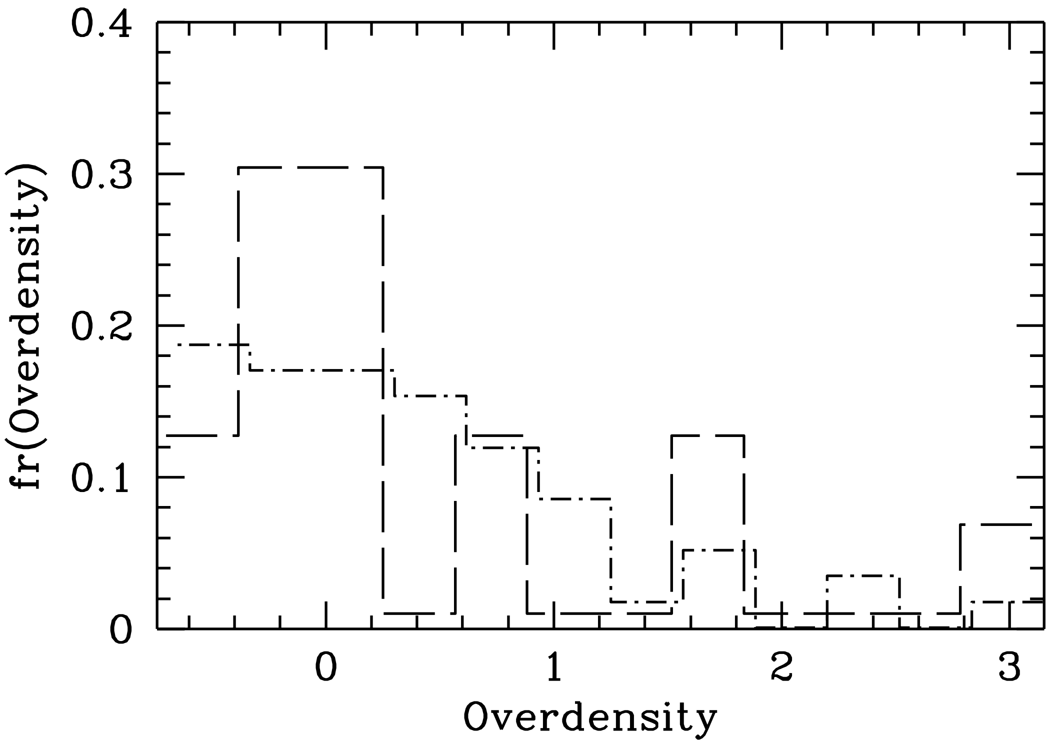
Vradial histogram



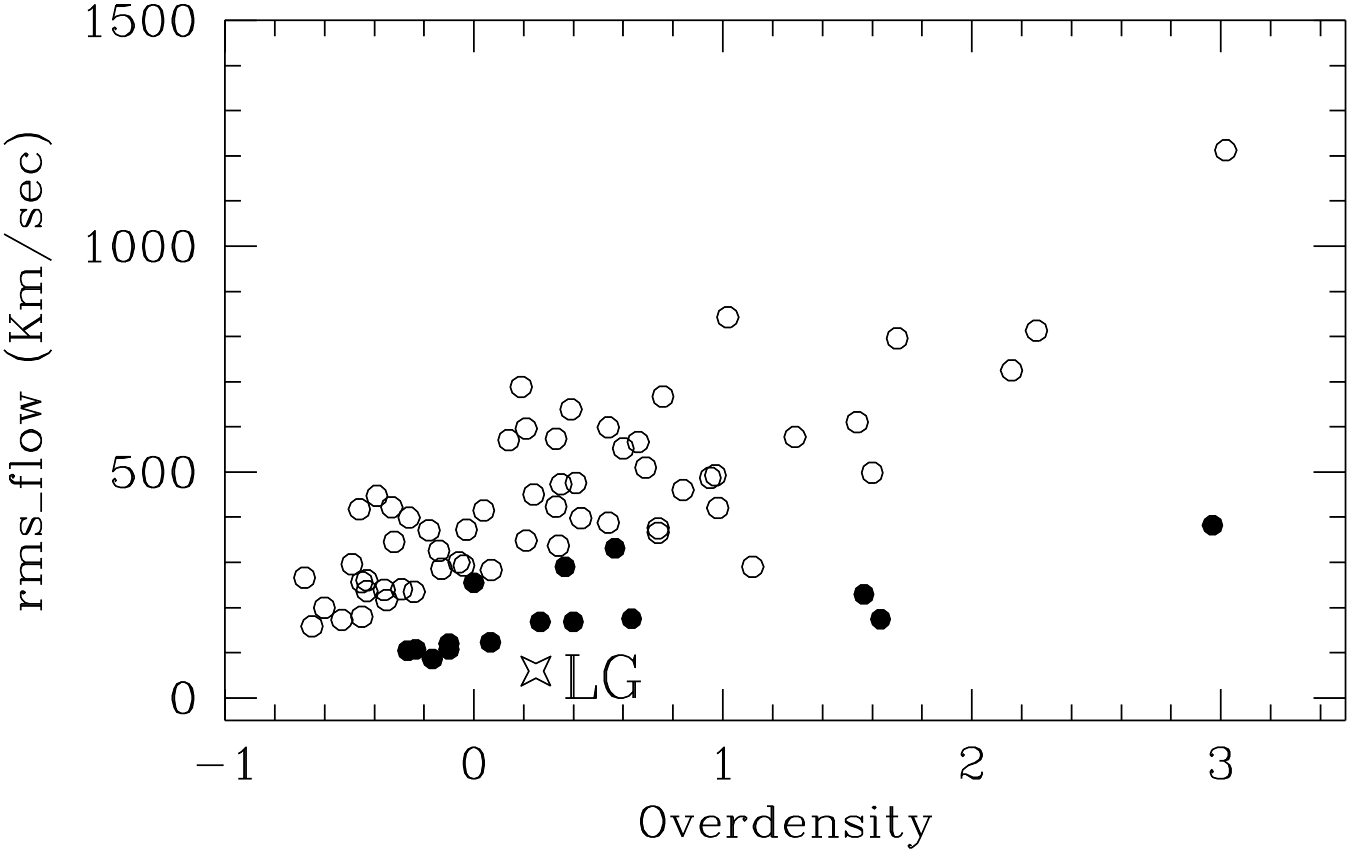

(a)
radial velocity (km/sec)
1000
500
0
−500
−1000
0
500
1000
1500
separation (kpc)
(b)
radial velocity (km/sec)
1000
500
0
−500
−1000
0
500
1000
1500
separation (kpc)

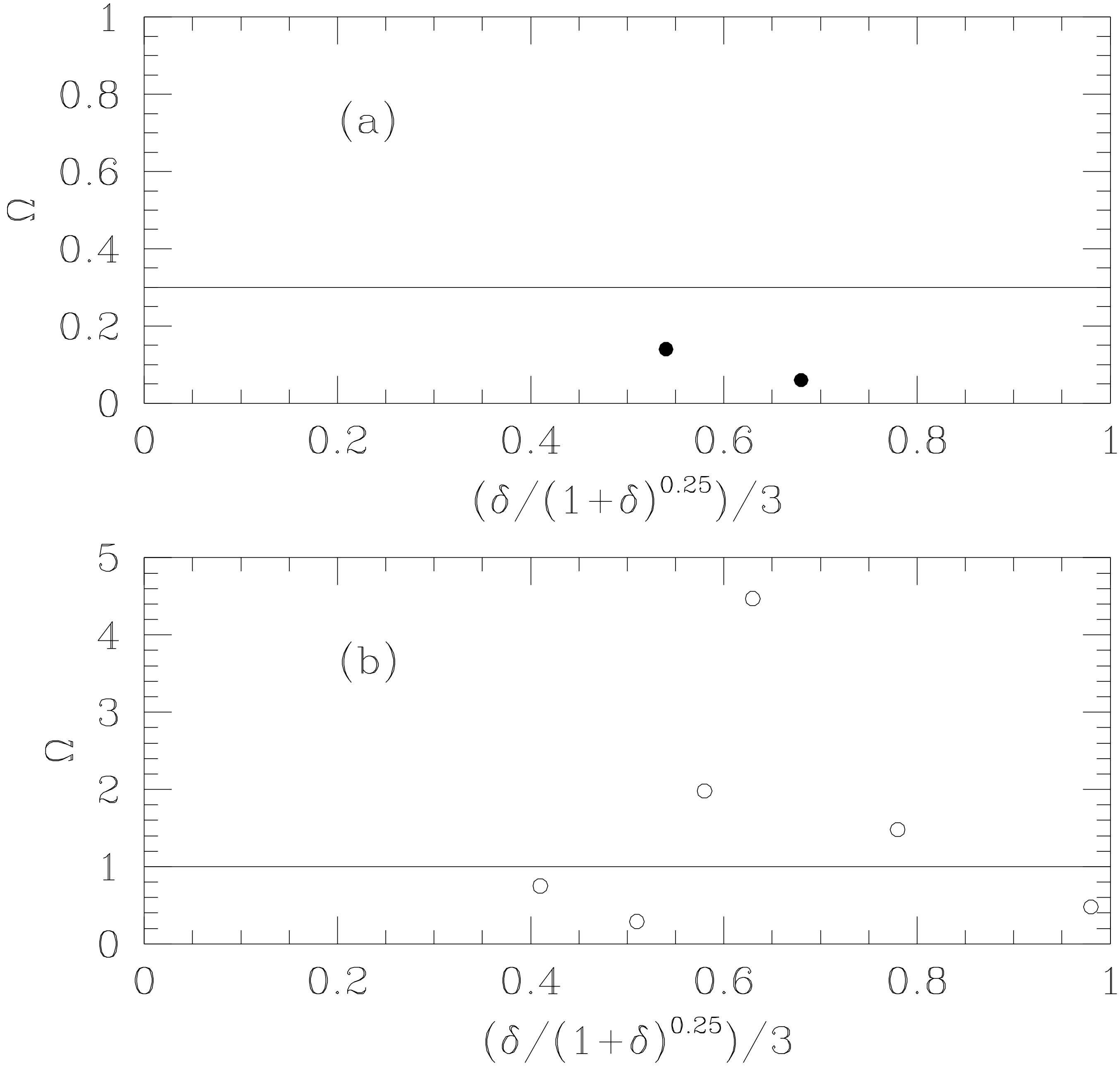
Vr/V histogram



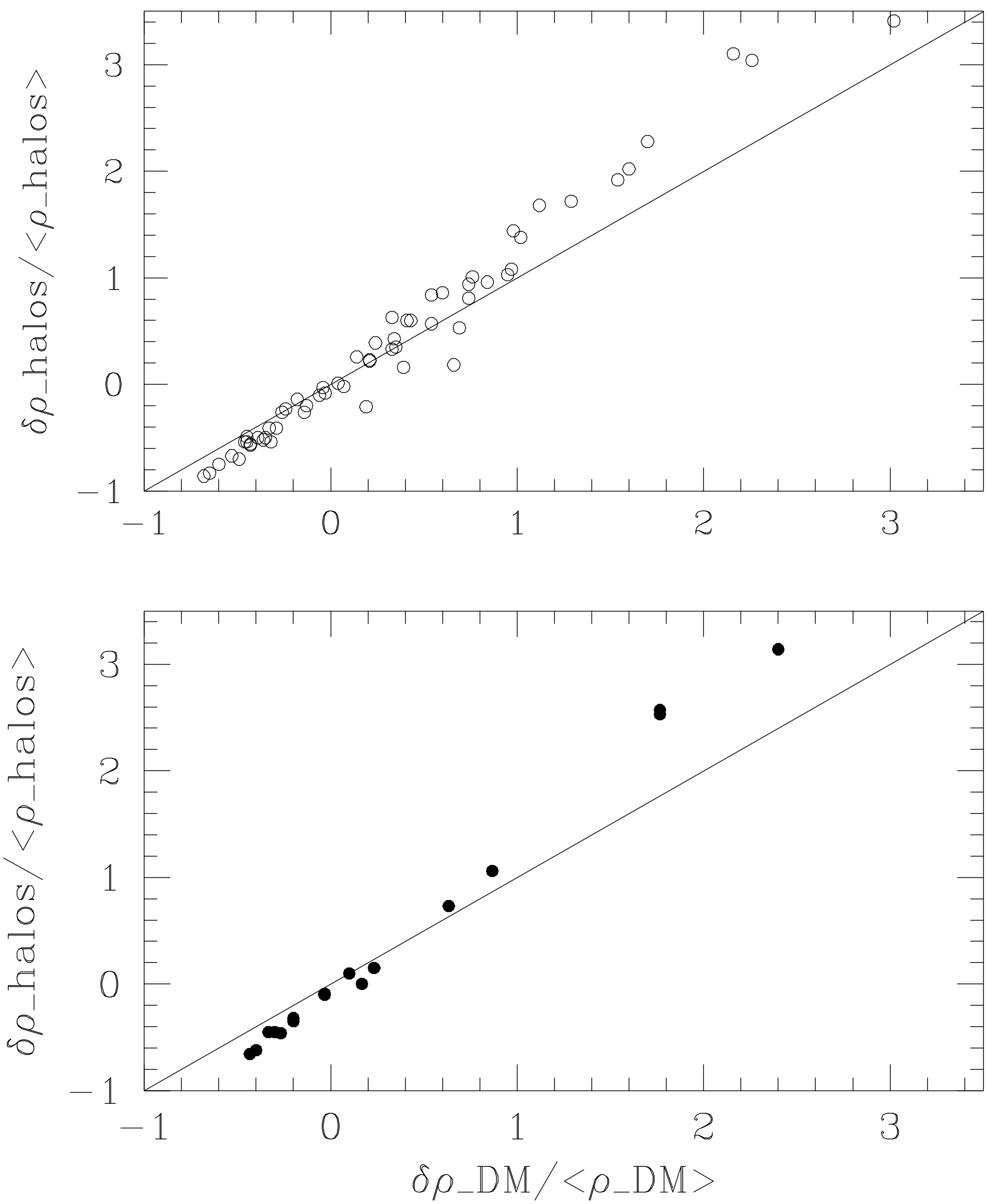


0.4
0.3
0.2
0.1
0
fr(Overdensity)
0
1
2
3
Overdensity


1500
1000
500
0
rms_flow (Km/sec)
−1
0
1
2
3
Overdensity
LG



(a)
Ω
0
0.2
0.4
0.6
0.8
1
$(\delta/(1+\delta)^{0.25})/3$
(b)
Ω
0
1
2
3
4
5
0
0.2
0.4
0.6
0.8
1
$(\delta/(1+\delta)^{0.25})/3$


δρ_halos/<ρ_halos>
δρ_halos/<ρ_halos>
δρ_DM/<ρ_DM>
−1
0
1
2
3